# INVESTIGATION OF REGIONAL SOURCE PROPERTIES OF THE UNDERGROUND NUCLEAR EXPLOSION IN NORTH KOREA

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## ABSTRACT

We explore the source properties of the October 9, 2006, underground nuclear explosion (UNE) in North Korea from regional phases. The dense seismic stations deployed in South Korea, Japan, and China provided us unique regional observations of the UNE. The unique data set allows us to investigate the source properties by regional phases. The isotropic moment of UNE is estimated by $2.9 \times 10^{14}$ Nm from long-period waveforms. The source spectra of regional phases from the UNE are inverted. We determine the apparent moment, corner frequency, overshoot parameter, attenuation factors, and frequency power-dependence terms from the inversion. We present the inverted source spectra with comparison of theoretical source-spectral models. The inverted source spectra agree well with theoretical curves based on UNE source-spectral models. We find that the overshoot parameters of P phases are determined as close to those from theoretical UNE source-spectral models. On the other hand, the overshoot parameters of S are determined close to zero. The low overshoot parameters for S phases suggest that their excitation sources may be different from those of P phases. We analyze the source spectra of natural earthquakes at a nearby location for comparison with those of the UNE. We test P/S spectral-amplitude ratios for discrimination between UNE and earthquakes.

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## OBJECTIVES

Despite a long-time monitoring of UNEs, the source-spectral properties of regional phases have not been fully understood due to lack of regional seismic observations. The October 9, 2006, UNE test in North Korea provides us a unique chance to investigate the source properties of UNE from regional phases. We study the source properties by inverting the source spectrum and overshoot parameter from regional waveforms. We also test the P/S spectral-amplitude ratio method for discrimination of UNE from natural earthquakes.

## RESEARCH ACCOMPLISHED

We investigate the source properties of regional phases from the UNE in North Korea. We compare the source properties between UNE and natural earthquakes. For the comparison, we also analyze a nearby earthquake with a magnitude of 4.2 that occurred in April 16, 2002. The magnitude of the earthquake is comparable to that of the UNE.

### Estimation of Moment

We collect seismic records from 48 broadband seismic stations deployed in South Korea, Japan, and China. The distances between the UNE and stations are 300–1100 km (Figures 1 and 2).

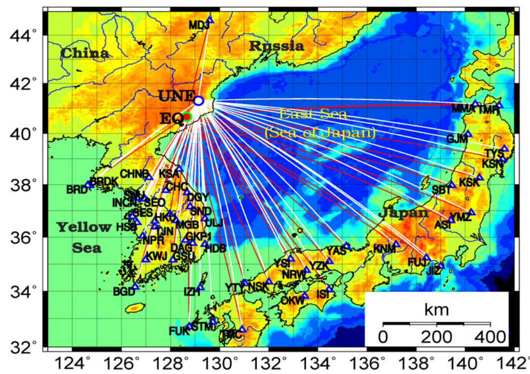


**Figure 1. Map of events (circles) and stations (triangles). The two events are the October 9, 2006, UNE and a nearby $m_b$ 4.2 earthquake (EQ).**

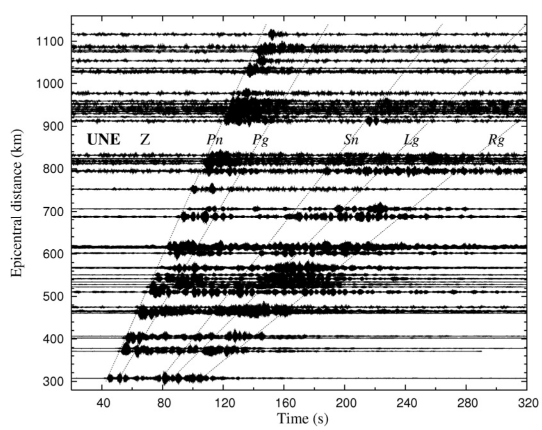


**Figure 2. Vertical seismograms of the UNE that are high-pass filtered above 2 Hz. Major regional phases are denoted.**

Long-period displacement waveforms are inverted for estimation of the moment of the UNE using the waveform inversion technique of Dreger and Helmberger (1993). We choose a frequency band in which signal-to-noise ratio is

sufficiently large. The waveforms of stations MDJ, DGY, CHC, and SEO in the frequencies of 0.05–0.1 Hz are analyzed for the inversion. The isotropic moment is estimated by $2.90 \times 10^{14}$ Nm (Figure 3). This estimate is approximately equivalent to $m_b$ of 4.4 (Patton and Walter, 1993). Also, the estimate is comparable to the regional observation of Hong et al. (2008).

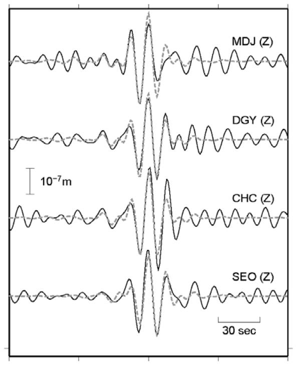


**Figure 3. Comparison of vertical displacement waveforms between observed (black) and synthetic (dotted gray) seismic records with estimated moment. The synthetic waveforms agree well with the observations.**

## Inversion of Source Spectra

The amplitude of phase can be expressed by (Sereno et al., 1988; Taylor and Hartse, 1998; Xie and Patton, 1999):

$$A_i(f)=S(f)G(d_i)\exp[-\pi f\, d_i/(v_g Q_i(f))]e_i(f), \tag{1}$$

where $A_i(f)$ is the ground motion at station $i$ at the frequency of $f$, $S(f)$ is the source spectrum, $G(d_i)$ is the geometrical spreading term for the distance of $d_i$, $Q_i(f)$ is the attenuation factor on the ray path to station $i$, $v_g$ is the group velocity of the phase, and $e_i(f)$ is the cumulative effect of the other minor factors along the ray path. Here, the source spectrum model, $S(f)$, is different between UNE and natural earthquakes (see Sereno et al., 1988). We apply an inversion scheme that is modified from Xie and Patton (1999). In the inversion, we consider that the overshoot parameter is an unknown. Thus, we invert for the source spectra of regional phases by determining the moment, corner frequency, overshoot parameter, reference quality factors, and power-law frequency dependence terms. The detailed procedure is described in Hong and Rhie (2008).

From the inversion, we find that the Pn source spectrum of the UNE shows an apparent moment ($M_0$) of $6 \times 10^{14}$ Nm, corner frequency ($f_c$) of 5.4 Hz, and overshoot parameter ($\xi$) of 1.4. For Lg, we have $M_0 = 2 \times 10^{13}$ Nm, $f_c = 1.0$ Hz, and $\xi = 0.1$ (Figure 4). The estimated Pn overshoot parameter is close to those conventionally adopted, while the estimated Lg overshoot parameter is lower. On the other hand, the apparent moment and the corner frequency of Pn source spectrum of the earthquake are $M_0 = 2 \times 10^{15}$ Nm and $f_c = 5.8$ Hz. The Lg source spectrum of the earthquake shows $M_0 = 4.8 \times 10^{13}$ Nm and $f_c = 2.1$ Hz. The apparent moments of Pn and Lg spectra of the earthquake are estimated higher than those of the UNE.

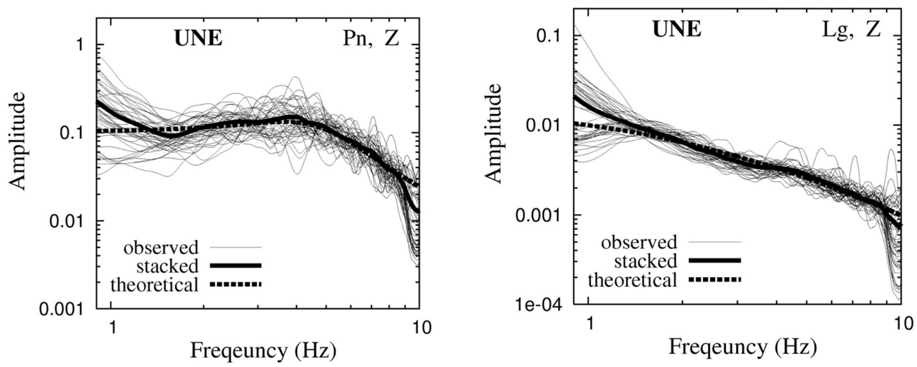


**Figure 4. Pn and Lg source spectra of the UNE. The Pn phase displays the characteristic overshooting feature, while the Lg phase decreases with frequency monotonically.**

### Pn/Lg Spectral-Amplitude Ratio

The Pn/Lg spectral-amplitude ratios of the UNE increase in the frequencies lower than the Pn corner frequency and increase in the frequencies higher than the corner frequency (Figure 5). This form is different from the spectral-amplitude ratio of the earthquake, which displays monotonic increase with frequency (figure is not presented). The observed P/S spectral-amplitude ratios of the UNE agree well with theoretical variation.

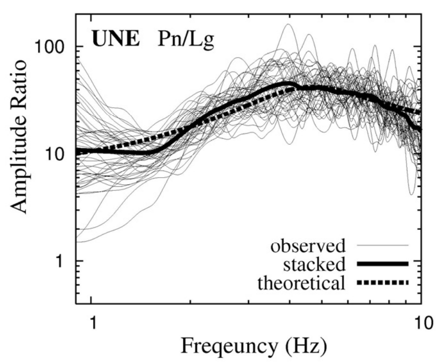


**Figure 5. Pn/Lg spectral-amplitude ratios of the UNE. The observed spectral-amplitude ratios agree well with the theoretical variation.**

## CONCLUSIONS AND RECOMMENDATIONS

Regional seismic records for the October 9, 2006, UNE in North Korea were inverted for investigation of source properties of regional phases. From a long-period waveform inversion, we estimated the isotropic moment of the UNE, which is given by $2.9 \times 10^{14}$ Nm. The source spectra of Pn and Lg phases were inverted with determination of apparent moment, corner frequency, and overshoot parameter. The dense observation allowed us to determine the overshoot parameter as an independent unknown. The estimated Pn overshoot parameter is estimated close to that conventionally assumed, while the Lg overshoot parameter is estimated lower. The observation suggests that the shear energy may be independent from the P-wave excitation source. The P/S spectral-amplitude ratios agree with theoretical expectation and appear to be useful for discrimination of UNE from earthquakes.

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